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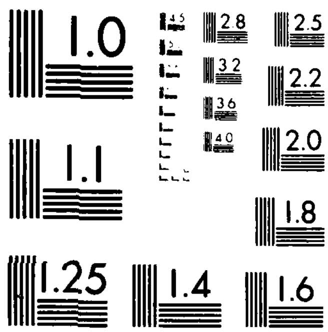

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Grant NGL 05-020-272
Grant NAGW-92

OFFICE OF NAVAL RESEARCH
Contract N00014-75-0673

PHYSICAL ASPECTS OF THE PREDICTION OF SOLAR FLARES

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ABSTRACT The properties of a solar flare depend critically on the preflare magnetic-field configuration and the way that this configuration evolves during the flare process. The flare process often, if not always, involves the eruption of a filament or similar structure, possibly leading to complete ejection from the sun. This eruption will generate an extensive current sheet: reconnection of this sheet contributes to the gradual phase and perhaps also to the impulsive phase. It is proposed that reconnection of a current sheet (pre-existing, or generated by filament eruption) is required for a gamma-ray event or a particle event. A particle event requires also an escape mechanism that could be provided either by a pre-existing open current sheet or by the ejection of the magnetic-field configuration associated with a filament. Following these guidelines, it is possible to propose a classification of flares into seven categories and to propose whether or not each category will lead to the following phenomena: mass ejection, shock wave, gamma-ray emission, and particle event.

1. INTRODUCTION

The development of flare theories and the development of procedures for flare prediction are both important components of solar physics that should be closely related but seem to have proceeded almost independently. The purpose of this talk is to summarize my current views about the processes involved in solar flares and to suggest developments in prediction procedures that are suggested by these views.

In Section 2, I present a summary of ideas produced in more detail elsewhere (Sturrock et al. 1984) concerning energy storage and the various mechanisms of energy release involved in flares. Certainly in large flares, and possibly in small flares also, the primary process appears to be the eruption of a filament, the flare itself representing a by-product of this eruption.

Based on the views expressed in Section 2, one may categorize flares according to the pre-existing magnetic field configuration, whether or not a filament is involved, and, if a filament is involved and erupts, whether the eruption is partial or complete (representing an expulsion from the sun's atmosphere). One may speculate about the plasma processes that would take part in each

configuration, and on the resulting observable manifestations of the flare, in particular, whether the flare would produce a gamma-ray event, a particle event, or an interplanetary disturbance.

Based on the ideas advanced in Sections 2 and 3, one may speculate on the possible procedures that might lead to improved methods for predicting solar flares, including prediction of the type of solar flare that might occur.

2. STORAGE AND RELEASE

It is generally agreed that energy released during a flare has been stored in the form of a stressed magnetic-field configuration, and that the energy release process that produces a flare involves magnetic-field reconnection (Priest 1976; Svestka 1976; Sturrock 1980). However, flares vary greatly in their characteristics, and a typical flare is in itself a complex phenomenon.

In a recent article (Sturrock et al. 1984), Kaufmann, Moore, Smith, and I have argued that energy release in a flare occurs on four characteristic time scales: (a) on the sub-second time scale of "sub-bursts" that are a prominent feature of millimeter microwave records; (b) on the few-second time scale of "elementary bursts" that are a prominent feature of hard X-ray records; (c) on the few-minutes time scale of the impulsive phase; and (d) on the tens-of-minutes or longer time scale of the gradual phase.

We propose that the development of the impulsive phase of a flare, including energy release on time scales (a), (b), and (c) is strongly influenced by the concentration of magnetic field into "magnetic knots" at the photosphere. As a consequence, the coronal magnetic-field configuration may be pictured as an array of "elementary flux tubes" (Figure 1).

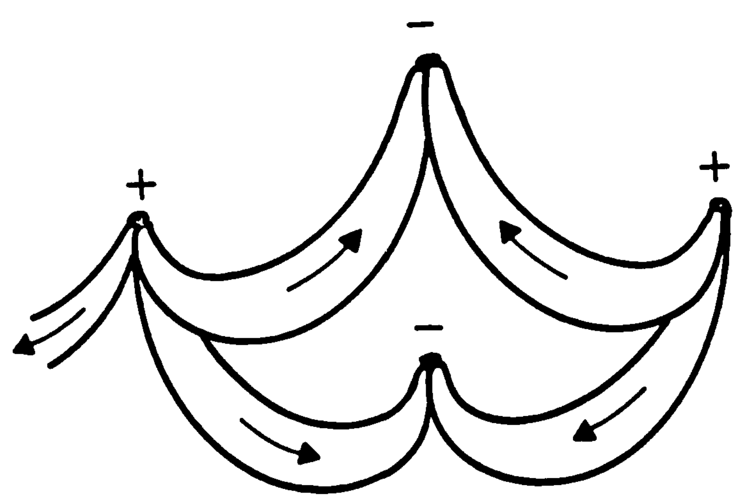

Figure 1. Schematic representation of possible coronal magnetic field structure, determined by the aggregation of photospheric magnetic field into discrete knots.

The release of the free energy in any single elementary flux tube may produce one of the "elementary bursts" that are prominent in hard X-ray data (van Beek et al. 1974). Observations show that, at the photospheric level, magnetic field lines tend to be pulled together into small flux regions with dimensions of order 500 km or less, in which the magnetic field strength is of order 1,000 to 1,500 gauss (Sheeley 1981). In consequence, the magnetic field of the photosphere tends to be aggregated into "knots" in which the flux has values of order $10^{18.4}$ Mx. The free energy U (erg) stored in a single flux tube may be estimated from calculations presented by Sturrock and Uchida (1981):

$$U = \frac{\Phi^2 (\Delta\chi)^2}{16 \pi^2 L} , \tag{2.1}$$

where Φ(Mx) is the magnetic flux, L (cm) is the length, and $\Delta\chi$ (radian) is the angle of relative rotation of the ends of a tube. MHD stability considerations suggest that $\Delta\chi$ is limited in its maximum value to 2π. On adopting this value as determining the maximum free energy that can be stored in such a flux tube, and on adopting the value $\Phi = 10^{18.4}$, we find that

$$U = 10^{36.2} L^{-1} . \tag{2.2}$$

We see that a reasonable range of lengths $L = 10^8 - 10^{9.5}$ for the region responsible for the impulsive phase of a solar flare leads to the range $U = 10^{26.5} - 10^{28}$. This agrees fairly well with the estimate $10^{27} - 10^{29}$ erg for the energy associated with elementary bursts (van Beek et al. 1974).

We find that the expected energy release time scale for such tubes is of the order 2 - 10 s, agreeing favorably with the typical duration of elementary bursts. The sub-bursts, with time scales of order 10^{-1} s, may be understood as resulting from the development of "magnetic islands" during the reconnection process (Spicer 1977; Carreras et al. 1980, 1981).

If a flare begins with energy release in a single elementary flux tube, the resulting disturbance of that tube may trigger energy release in adjacent elementary flux tubes. If this process continues in a sequential manner, energy stored in a large number of elementary flux tubes will be released within a few minutes. This is our interpretation of the impulsive phase of a solar flare.

The gradual phase of energy release of a solar flare, with a time scale of tens of minutes or longer, is attributed to energy release by reconnection of a large-scale magnetic-field configuration. This may be the still-stressed magnetic field left behind by the impulsive phase, but with greatly reduced current densities. However, in large flares such as two-ribbon flares, the gradual phase may be understood as being due to energy release in a large current sheet that has been produced by the eruption of a filament. The filament itself is regarded as resembling a rope with many strands, each strand being an elementary flux tube, the feet of all these tubes being near the polarity reversal line (Figure 2). The onset of a flare represents the occurrence of reconnection between adjacent oppositely directed flux tubes, so disconnecting the filament from the photosphere (Figure 2). The end result of this process is the formation of a single, long flux rope rooted only at its

ends. This flux rope will then tend to rise, stressing the overlying magnetic field to produce a new current sheet, as shown in Figure 3.

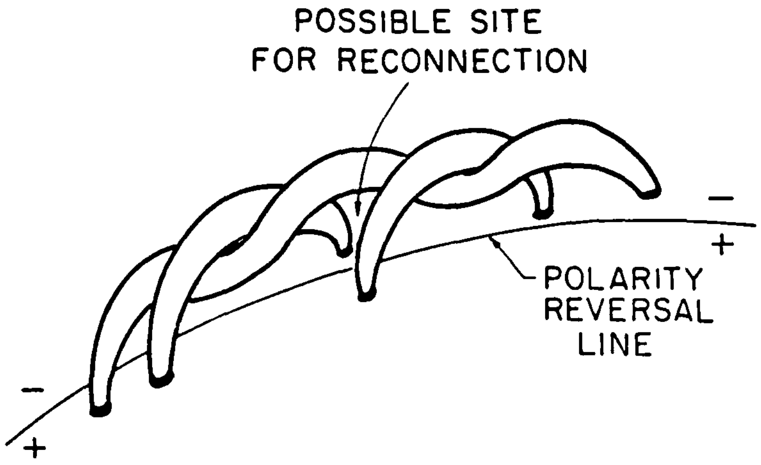

Figure 2. Schematic representation of possible magnetic field configuration of a filament.

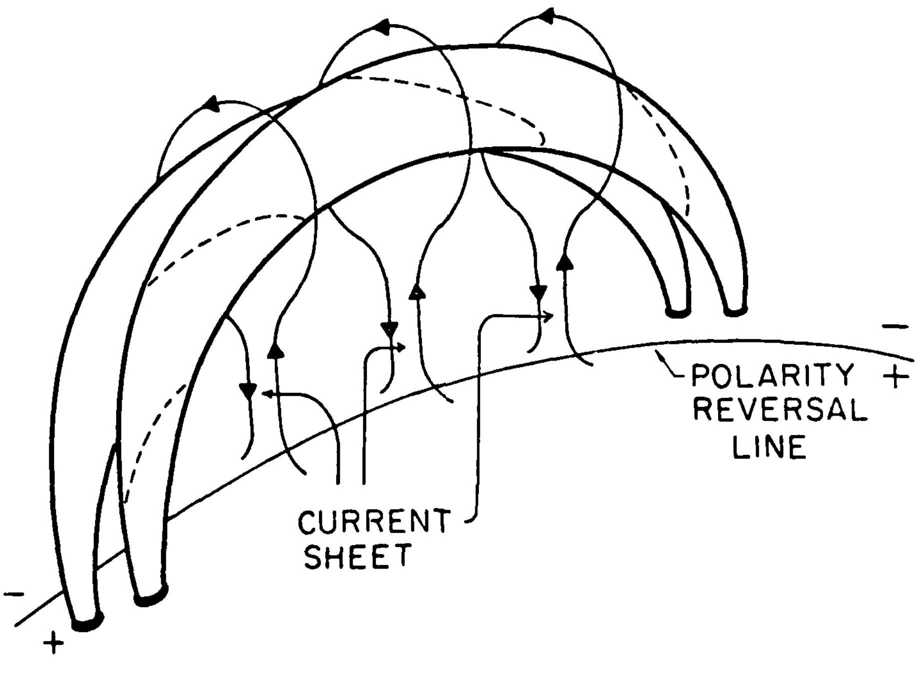

Figure 3. Schematic representation of the development of an extended current sheet beneath an erupting filament.

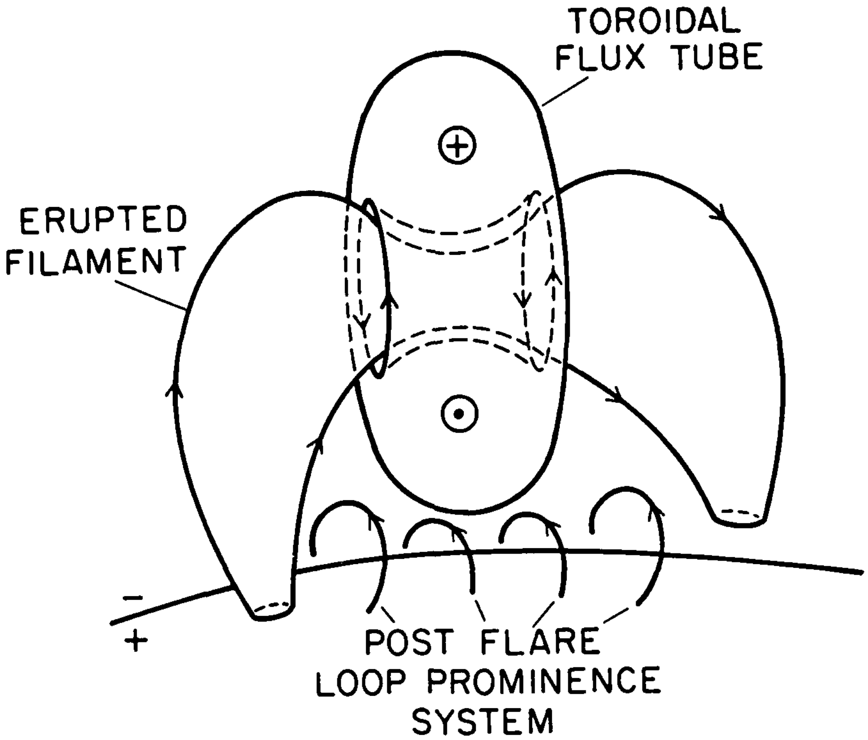

Figure 4. Schematic representation of a toroidal magnetic flux tube encircling an erupted prominence, as a result of the reconnection indicated in Figure 3. The toroid would be detectable as a stationary type IV radio burst.

Since this new current sheet is newly formed by a rapid process and extends to greater heights than the elementary flux tubes involved in the initial impulsive phase, it is likely to develop a high current density in a region of the atmosphere with low plasma density. This situation would appear to be favorable for acceleration of electrons and ions to high energy. Some of these particles will impinge upon the chromosphere to produce hard X-ray and possibly gamma-ray radiation, but some of the particles will be trapped in the newly produced, closed toroidal magnetic-field structures. High-energy electrons trapped in such a configuration (Figure 4) will produce microwave radiation and may produce long-lived hard X-ray emission. If the filament erupts completely into interplanetary space, the toroidal structure will expand with it. If this occurs, the particles will eventually be able to escape into interplanetary space, producing a high-energy event. If the expulsion is sufficiently rapid, a shock wave will develop ahead of the expanding plasmoid, to produce a type II radio burst (see Figure 5).

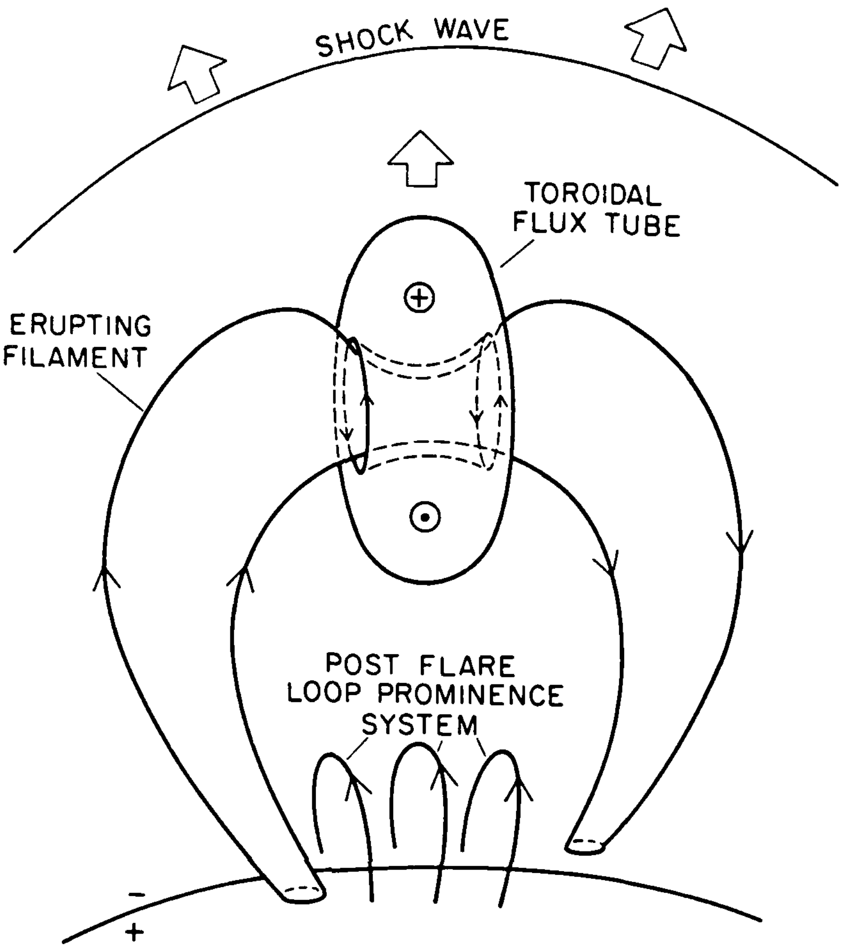

Figure 5. Schematic representation of situation that arises when a filament, encircled by a toroidal flux tube, is completely ejected from the sun. The toroid would be detectable as a moving type IV radio burst. The shock wave would give rise to a type II radio burst.

3. CATEGORIES OF MAGNETIC STRUCTURES AND PROPERTIES OF THE RESULTING FLARES

We have seen in the previous section that the different phases of a flare may be interpreted in terms of the evolution of the magnetic field structure. However, in the case that a flare is accompanied by a filament disruption, the evolution of the magnetic field is closely related to the behavior of the filament. Hence our first classification of possible flares is by the breakdown F,$\bar{F}$. We use the symbol F if a filament is involved in the flare process, and we use the symbol $\bar{F}$ if no filament is involved. Note, however, that it is difficult to be sure that no filament or no filament-like object is involved in a flare. Zirin (1983) has expressed the conjecture that in *every* flare there is a dark feature that is disrupted during the flare. Note also that there might be a similar rope-like magnetic-field configuration that, for one reason or another, has not collected cool gas and therefore does not manifest itself as an absorption feature.

If a filament is involved in the flare process, we assume that it will erupt as discussed in Section 2. However, there are two possible forms of eruption: we use E to indicate that the filament is ejected completely from the sun, and we use $\bar{E}$ to indicate that the filament erupts but is not ejected from the sun.

Finally, we introduce another classification characterizing the pre-existing magnetic-field configuration. We entertain three possibilities: N, that there is no significant current sheet associated with the pre-flare configuration; C, that there is a closed current sheet; and O, that there is an open current sheet (that extends into interplanetary space).

Our speculations concerning the behavior of flares, categorized in this manner, are shown in Table I. Note that the categories $F\bar{E}N$ and FEN do not appear since, if there was a filament, there must be a current sheet separating the magnetic field of the filament from the ambient magnetic field. However, it is also possible that the current sheet is open or partially open. Note also that, if a filament is involved and is ejected completely from the sun, the form of the pre-existing magnetic field is unimportant in the sense that the flare will have the same properties whether or not the initial current sheet was completely closed or partially open.

Table I. Categories of Magnetic Structures and Properties of Resulting Flares

	FN	FC	FO	FEC	FEO	FEC	FEO
Mass Ejection	X	X	X	X	X	✓	✓
Shock Wave	X	X	X	✓	✓	✓	✓
Gamma-Ray Emission	X	✓	✓	✓	✓	✓	✓
Particle Event	X	X	✓	X	✓	✓	✓

$\bar{F}$: no filament
F: filament
$\bar{E}$: filament eruption, but no ejection
E: filament ejection
N: no current sheet
C: closed current sheet
O: open, or partially open, current sheet

We now discuss these various categories of flare configuration in terms of four possible consequences of the flare: whether or not the flare produces (a) mass ejection that might produce a geomagnetic storm if it arrives at the earth, (b) a shock that might produce a type II radio burst, (c) gamma-ray emission, and (d) a particle event.

In relating the above effects to different types of flare, we make the following assumptions. Since the gamma-ray continuum is produced by MeV electrons and gamma-ray lines by MeV protons, we assume that this acceleration is produced by a process that does not occur in every flare. We assume that MeV particles are produced during the initial stages of reconnection of a current sheet that extends high in the corona. We assume that the eruption of a filament may produce a weak shock wave by the blast-wave process; however, the ejection of a filament may produce a stronger shock wave by the bow-shock process. In order for there to be a particle event, we assume that there must be conditions favorable for acceleration (required also for a gamma-ray event), but there must also be a mechanism for the particles to escape. This may be due either to a pre-existing open current sheet, or to the ejection of a filament that leads to the ejection of plasma, magnetic field, and high-energy particles. We attribute mass ejection simply to the ejection of a filament.

$\bar{\mathrm{F}}\mathrm{N}$: There is no filament and no current sheet. In this case, there is no mass ejection, no shock, no gamma-ray event, and no particle event.

$\bar{\mathrm{F}}\mathrm{C}$: There is no filament, but there is a closed current sheet. In this case, particle acceleration could occur giving rise to a gamma-ray event, but there would be no escape of particles, so there would be no particle event.

$\bar{\mathrm{F}}\mathrm{O}$: There is no filament, but there is an open current sheet. In this case, acceleration could occur to produce a gamma-ray event, and some of these particles could escape to produce a particle event.

$\mathrm{F}\bar{\mathrm{E}}\mathrm{C}$: There is a filament that erupts but is not ejected; the current sheet is closed. In this case, there would be no mass ejection, there could be a shock produced by the blast-wave mechanism, there may be a gamma-ray event, but there would be no particle event since there is no mechanism for particle escape.

FEO: There is a filament that erupts, and a current sheet is partially open. The results are similar to the results of $\mathrm{F}\bar{\mathrm{E}}\mathrm{C}$, except that there is now an escape mechanism so that there could be a particle event.

FEC: There is a filament that is ejected from the sun, but the initial current sheet is closed. In this case, there would be mass ejection, and there could be a strong shock produced by the ejection. There could be a gamma-ray event, and there could also be a particle event since particles may now escape into interplanetary space.

FEO: The only difference between the manifestation of this configuration and of FEC is that there could be prompt escape of particles from the pre-existing current sheet rather than a delayed particle event due to the ejection of the filament and magnetic field into interplanetary space.

4. POSSIBLE DEVELOPMENTS IN FLARE PREDICTION

We now inquire into what procedures might be explored for possible improvement in flare prediction, including the possible prediction of the type of flare to be produced.

Since filaments, or filament-like structures, play a key role in most important flares, and possibly in all flares, it would seem desirable to find some way to detect those filament disturbances that are known to be precursors of flare activity (Smith and Ramsey 1964). This could perhaps be achieved by automated spectroscopic data collection. If, for each pixel, the magnetic field is measured, the $H\alpha$ line is determined to be in emission or absorption, and the line-of-sight velocity of the $H\alpha$ line is measured, the system could alert the operator when a pixel displays simultaneously strong magnetic field, $H\alpha$ in absorption, and $H\alpha$ doppler shift.

The energy released during a flare is derived from the free energy of the magnetic field, and this free energy is produced by shear-like photospheric motion. Hence it would be highly advantageous to develop a technique for monitoring the photospheric velocity field in active regions. Since one needs to be able to monitor regions near the center of the disk, the technique cannot be based on doppler measurements. One possible procedure is to develop software that extracts the gross velocity field from a sequence of white-light maps (in digitized form) by using correlation techniques or following the motion of individual elements. If a suitable technique can be developed, this information, together with information on the line-of-sight magnetic field, should make it possible to make reasonable estimates of the free energy being stored in the magnetic field.

In the long run, one would like to develop a procedure for computing the coronal magnetic-field configuration from observational data. Even ignoring the complexity of current sheets, one must expect that the magnetic field will involve currents although it may be approximately force-free. Hence, a first step in this direction would be to find a procedure for computing force-free magnetic fields from observational data. This involves two distinct problems, one of data collection, and the other of computing.

The line-of-sight component of magnetic field is not sufficient to determine a force-free magnetic-field configuration. However, the field would be determined, in principle, if one could determine also the "magnetic connectivity"; that is, if one had some way of identifying which pairs of points in an active region are linked by magnetic field lines. R. Bogart, S. Antiochos, and I are working in collaboration with J. Harvey at Kitt Peak National Observatory, exploring the possibility that one can determine magnetic connectivity by searching for correlations in the brightness and velocity field of the upper chromosphere.

Measurement of the complete vector magnetic field, using a vector magnetograph such as that in operation at Marshall Space Flight Center (Hagyard _et al_. 1984) should in principle give sufficient information to determine the force-free magnetic field although the data is not in a form that is quite as convenient for computational purposes.

If one adopts the "constant-α" approximation, assuming that the current density is proportional to the magnetic field strength, then the equations for the force-free magnetic field reduce to a linear equation that can be solved without great difficulty. However, this assumption is quite restrictive, and it is essential to find a practical procedure for computing three-dimensional nonlinear force-free magnetic-field configurations.

It is clear that the goal of improving our techniques for predicting solar flares offers great challenges to observers and theorists alike.

This work was supported in part by NASA Grants NGL 05-020-272 and NAGW-92 and Office of Naval Research Contract N00014-75-0673.

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